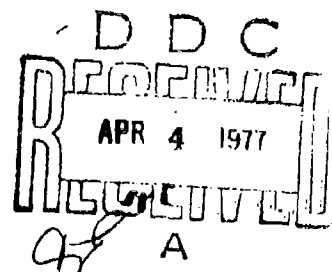AFCEC-TR-76-47

PREDICTION OF TEST CELL VISIBLE EMISSIONS

DIRECTORATE OF ENVIRONICS

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APR 4 1977
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DECEMBER 1976

FINAL REPORT : JUNE 1976 - NOVEMBER 1976

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(AIR FORCE SYSTEMS COMMAND)
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A theoretical correlation between jet engine test cell plume opacity and Society of Automotive Engineers (SAE) engine smoke number (SN) was developed. Intermediate results provide soot loading at the exhaust plane of the engine, engine exhaust flow rates and test cell total air flow rate. The specific particle extinction coefficient which correlates light scattering properties with soot loading is the most difficult parameter to → next page

cont

20 (continued).

define. A value predicted from Mie theory is used for
correlations close to the exhaust plane of the engine. At
the exit plane of the exhaust stack agglomeration and scouring
change the particle size distribution and individual particle
density so that theoretical prediction is difficult. The
value for specific particle extinction coefficient at the
exhaust stack was chosen based on what little empirical data
was available. When additional data becomes available, it
should be possible to define this parameter more precisely.

cont.

PREFACE

This study was performed under Program Element 63723F, AFCEC JON 21037A29. The project engineer and author is Major Samuel P. Finch, III, Assistant Professor of Chemistry, Department of Chemistry and Biological Sciences, USAF Academy, Colorado. He performed this work at the Air Force Civil Engineering Center, Tyndall Air Force Base, Florida, under the AFOSR Summer Faculty Research Program. Inclusive dates of Major Finch's work were 7 June 1976 to 16 July 1976.

Captain Arland W. Eyl, Jr is coauthor. He refined the methodology and developed a computer program to perform the calculations. This refinement took place between August and November 1976. The authors wish to thank Major Peter S. Daley for technical assistance.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECTION I

ESTIMATION OF TEST CELL PLUME OPACITY

To insure Air Force facility compliance with applicable federal, state, and local air pollution regulations, it is necessary to estimate the opacity of plumes emitted by jet engine test cells. Since Ringelmann readings are subjective and somewhat inaccurate (Reference 1), and the costs of installing a transmissometer or making visual readings on each facility is high, a theoretical method using known engine and test cell parameters is desirable. There is no known work which relates engine particulate emission taken at the exhaust plane of the engine to the plume opacity at the exit plane of the test cell exhaust stack. However, there are several works that deal with intermediate portions of the required calculations.

The smoking tendency of jet engine exhausts is most commonly reported in terms of smoke number (SN) computed in accordance with the Society of Automotive Engineers ARP 1179 (Reference 2). Several published works have related the SN to the optical properties at the exhaust plane of the engine (References 3 to 7). These have resulted in good correlations with the experimental results reported by Shaffernocker and Stanforth (Reference 5). Wood (Reference 3) has done the latest work in this area, and his work is the basis for present relationships correlating the soot loading at the exit plane of the engine with opacity using the Beer-Lambert Law.

In each test cell there is substantial additional air flow around the engine that dilutes the emissions. To predict the opacity of the plume as it leaves the exhaust stack of the test cell, it is necessary to know this air flow. The air flow can be calculated if the cell geometry and the pressure loss caused by the air flow through the cell is known.

As the particulate emissions move from the engine to the exhaust plane of the cell, they are affected by agglomeration and dilution. Also at higher engine exhaust flow rates larger particles are scoured from the walls of the cell. This causes a change in the mean particle size, the particle

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size distribution, and the density of the individual particles. The light scattering properties of the aerosol are predicted by Mie theory using particle size distribution and density. Ensor and Pilot (Reference 8) used particle size and distribution to derive a K factor to facilitate making Mie scattering theory predictions of plume opacity.

The purpose of this report is to describe a method for estimating test cell plume opacities based on available engine parameters, test cell geometry, and test cell pressure depression.

SECTION II

METHODS

Correlation of plume opacity with test cell and engine parameters involves four distinct elements. The first three elements, (1) conversion of SN to soot loading, (2) applying engine combustion parameters to obtain engine flow rates, and (3) using test cell geometry to determine total flow rates, provide the input variables for use in (4) the Beer-Lambert Law to make the final opacity estimation. Each element will be discussed independently then combined with the others to make the final calculation.

1. CONVERSION OF SN TO SOOT LOADING

SAE SN (Reference 2) is currently the most common method of reporting the concentration of carbon particles in the exhaust of a jet engine. The technique compares the reflectance of clean filter paper to the reflectance of a filter that has been stained by drawing a specific weight of engine exhaust gas through it. The loss of reflectance is a function of the amount of soot deposited on the paper. There have been numerous efforts to convert SNs to a soot loading in g/cm^3 at the exhaust plane of the engine, the latest by Wood in 1975. Wood combined the results of previous efforts to derive an equation that gives a good correlation with available empirical data. His equation is:

$$1 - \frac{SAE\ SN}{100} = \exp\left[-\left(\frac{W}{A} \cdot \frac{S_p}{C} \cdot \frac{\omega_e}{\rho_e}\right)^b\right] \qquad (1)$$

where

W — weight of gas sample used for smoke number determination (g)

A — area of filter spot (cm^2)

ω_e — soot loading at the exit of the engine (g/cm^3)

ρ_e — density of the exhaust gas (g/cm^3)

S_p — specific projected particle extinction area (cm^2/g)

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The constants b and C are empirically derived.

For   SN $\leq$ 15,   b = C = 1,   and

for   SN $\geq$ 40,   b = 0.48, and C = 3.14

W/A is the weight of the air sample in pounds per square inch of filter spot area. The SN is normally taken at a W/A of 0.0230 lb/in^2 (1.62g/cm^2). If no W/A is reported in the data for the engine, the above value should be used.

S_p is a number that relates the reduced reflectance of the stained filter paper spot to the mass loading on that spot. There are problems in finding a value for this parameter. There is some question as to whether the particle absorbs light on the filter paper the same way it would if it were an aerosol. The staining of the filter is also known to be nonlinear. The error associated with this problem has not been quantified but appears to be small. Wood (Reference 3) calculated a value of 8.64 x 10^4 cm^2/g using Shaffernocker's and Stanforth's (Reference 5) data. A theoretical value for S_p has been derived from the K parameter of Ensor and Pilot. Both Wood and Champagne (Reference 4) agree that the value derived from Mie theory (6 x 10^4 cm^2/g) gives the best overall results. This value will be used for converting SN to soot loading.

Wood's equation was rearranged in the form:

$$\frac{\omega_e}{\rho_e} \cdot \frac{W}{A} = \left[-\ln(1 - \frac{SAE\ SN}{100}) \right]^{1/b} \cdot \frac{C}{S_p}$$

and $\frac{\omega_e}{\rho_e} \cdot \frac{W}{A}$ in grams per cm was plotted against SN.

Figure 1 shows the results of this plot using S_p = 6 x 10^4 and the appropriate values for b and C. Figure 2 shows this same plot with a straight line between SN 70 and SN 15. The figure shows that a single straight line

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equation can be used to predict

$$\frac{\omega_e}{\rho_e} \cdot \frac{W}{A} \text{ in g/cm for SN} > 15 \text{ with little error.}$$

The equation of this straight line is:

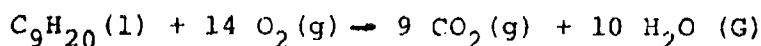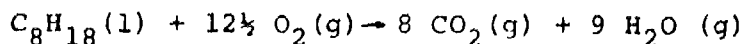$$\frac{\omega_e}{\rho_e} \cdot \frac{W}{A} = 10^{(0.0263(SN)-5.96)} \text{ g/cm} \qquad (2)$$

Using the known values of W/A, the ratio, ω_e/ρ_e, can be calculated. This value, the particulate mass fraction in the engine exhaust, can then be used in conjunction with the engine flow rates calculated in the next section to determine the rate of soot production in grams/sec. It is felt that engines producing SNs less than 15 will not exceed plume visibility standards in most test cells. However, if a soot loading is required for a SN less than 15, Wood's equation (1) using b = 1 and C = 1 will give the desired value.

2. ENGINE COMBUSTION PARAMETERS

Using SN to derive a soot loading at the exit plane of the engine results in grams of carbon per cubic meter of exhaust flow. The engine fuel flow, fuel to air ratio, and the stoichiometry of the fuel combustion equations are used to calculate the soot flow rate in grams per second.

The Wright-Patterson Air Force Base fuels lab reports JP-4 jet fuel is a mixture of 8 and 9 carbon saturated hydrocarbons with an average molecular weight of 120 A.M.U. The average molecular weight is the result of a weighted average mixture containing 57 percent C_9 chains and 43 percent C_8 chains.

The combustion of these two chains must be considered separately. Assuming complete combustion, the equations are:

$$C_8H_{18}(l) + 12\tfrac{1}{2} O_2(g) \rightarrow 8\ CO_2(g) + 9\ H_2O\ (g)$$

$$C_9H_{20}(l) + 14\ O_2(g) \rightarrow 9\ CO_2(g) + 10\ H_2O\ (G)$$
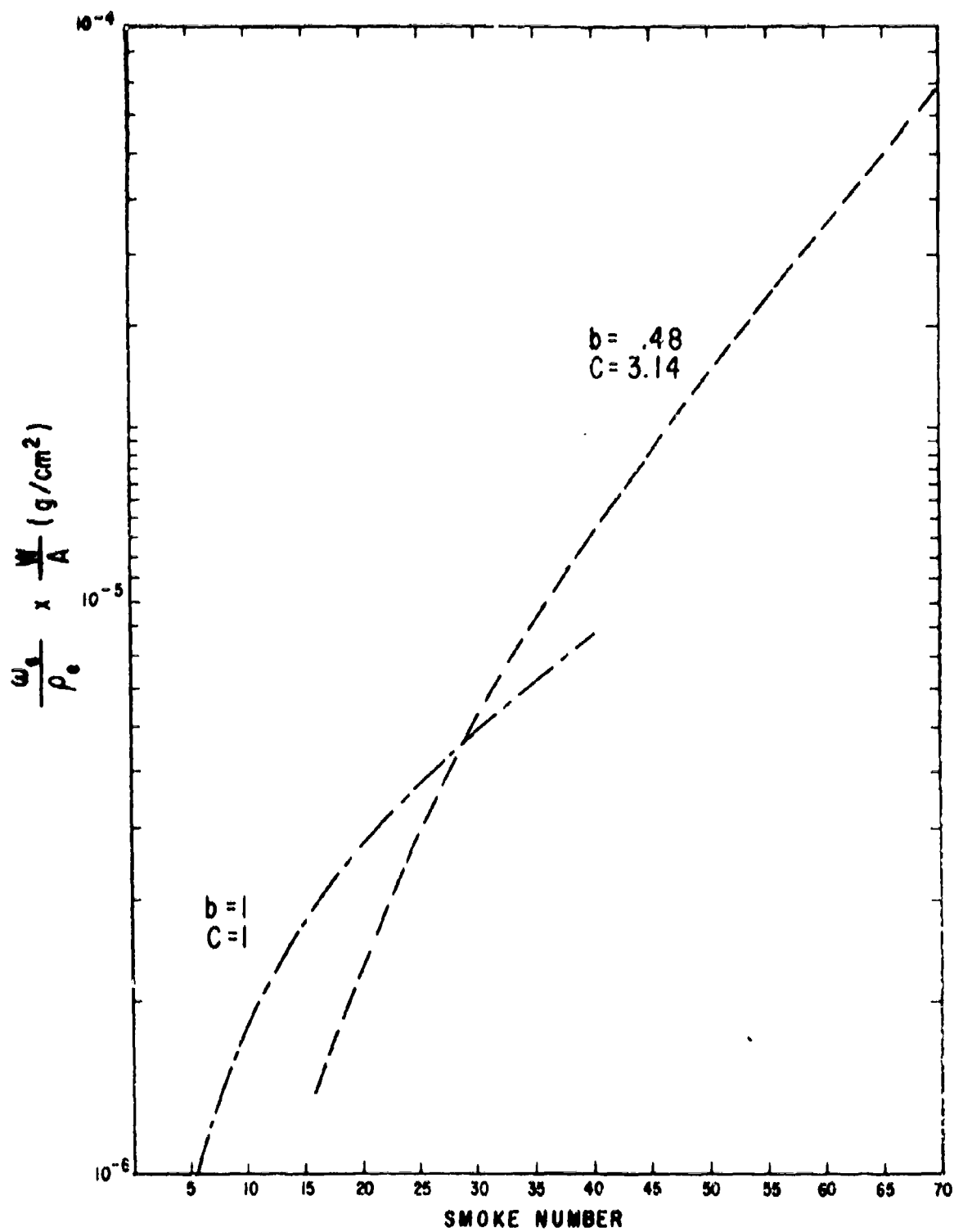
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Figure 1. Correlation Between Smoke Number
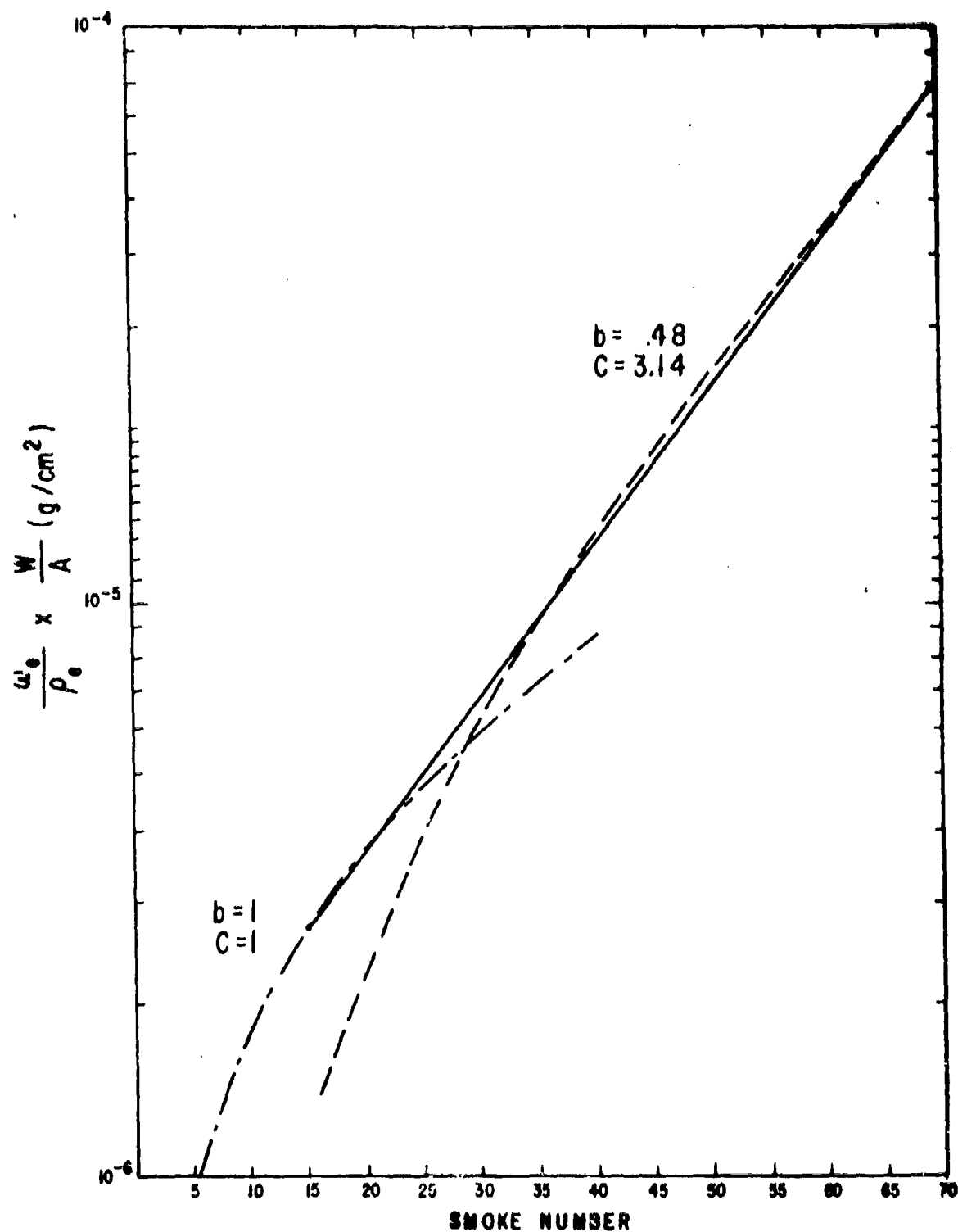and Soot Loading, using Wood's Equation

Figure 2. Smoke Number and Soot Loading Calculated from Wood's Equations with a Straight Line Interpolation between SN-15 and SN-70

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The combustion of the C_8 chain consumes 12.5 moles of gaseous oxygen and produces 17 moles of gaseous products. This is a net increase of 4.5 moles of products per mole C_8 fuel burned. The C_9 combustion results in a 5 mole increase per mole of C_9 fuel burned. Using the weighted average of $(.57)(4.5) + (.43)(5.0)$ results in the system producing 4.7 moles of product gases per mole of fuel burned. Using fuel flow in pounds per hour, and a known fuel/air ratio (use total fuel/air ratio for a turbofan engine) and a molecular weight of 28.95 AMU for air, the air flow and the fuel flow in moles per second are computed. The moles of fuel per second is multiplied by the stoichiometric relationship of 4.7 moles of gaseous products per mole of fuel burned to get the increase in gaseous products. This is added to the molar air flow to find the total number of moles per second flowing through the engine. Using the average molecular weight of 28.95 g/mole for air, the total exhaust flow in grams per second is found. If this is multiplied by the particulate mass fraction in the exhaust found in the previous section, the soot flow rate in g/m^3 is obtained.

The method described above was used to compute the soot flow rate in the sample calculations. The result was 1.45 g/sec, and for a similar engine Grems (Reference 9) reported 1.29 g/sec. This is a fairly good agreement because of relating particle extinction coefficients on filter paper to aerosol extinction coefficients.

3. TEST CELL AIR FLOW RATE

The total amount of air flowing through a jet engine test cell can be calculated by knowing the geometry of the cell, and the pressure loss between the air inlet and the engine air intake caused by the air's movement through the cell. A typical test cell is shown in Figure 3.

Three areas are referenced, and an average velocity is associated with each. Area B is the entry baffles, area E is a square or mitered elbow, and area R is the reference area where the cell depression probe is located.

The ASHRAE Guide and Data Book (Reference 10) shows that incompressible flow may be assumed with less than 3 percent error when the ratio P_2/P_1 is 0.95 or greater. Since reported cell depression pressure ratios are generally 0.98 or greater, the basic Bernoulli equation for incompressible flow can be used to determine the velocity of the air flow at the inlet of the engine.

INLET

$A_0 = \infty$
$V_0 = 0$

EXHAUST

A_B
V_B

A_E
V_E

L_1

L_2

$V_R \; A_R$

ENGINE

DIFFUSER
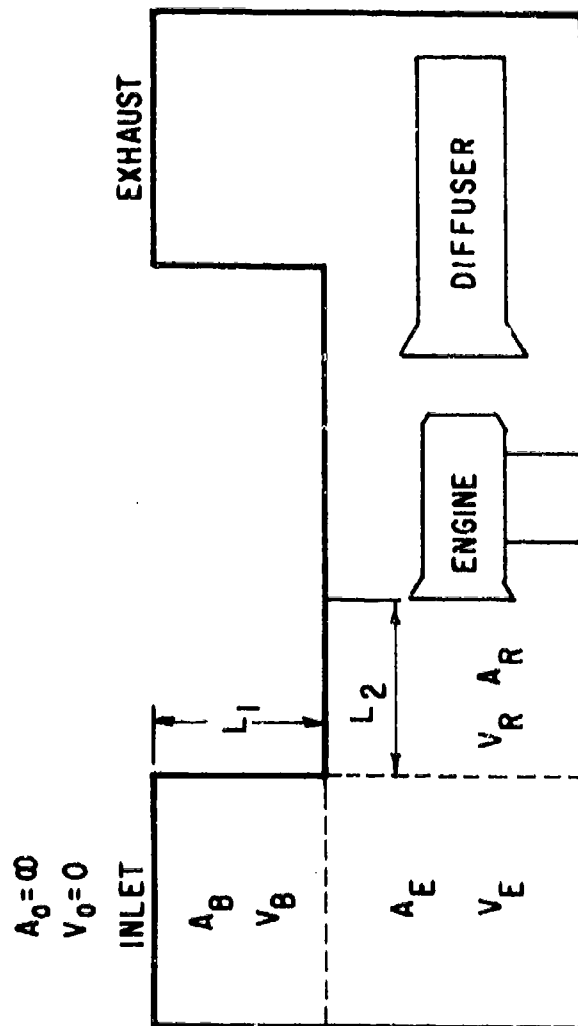
Figure 3. Typical Jet Engine Test Cell. Subscripts indicate: o-ambient conditions, B-baffles section, E-elbow section, R-reference section. L-1 and L-2 are required dimensions.

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The equation used is:

$$\frac{\bar{V}_o^2}{2g_c} + Z_o + \frac{P_{s_1}}{\rho} = \frac{\bar{V}_R^2}{2g_c} + Z_R + \frac{P_{s_2}}{\rho} + \text{losses}$$

where

$\bar{V}$ - average velocity in section being considered.

Z - elevation above datum plane.

ρ - density of air at reported cell conditions (Reference 11).

g_c - is the gravitational dimension conversion constant.

P_{s_1} - uncorrected barometric pressure.

P_{s_2} - uncorrected pressure at engine inlet.

$P_{s_1} - P_{s_2}$ - reported cell depression pressure in inches Hg or inches H_2O.

o subscript used to denote ambient conditions.

R subscript used to denote area around the engine air intake.

Because $\bar{V}_o = 0$ and the energy change due to changes in elevation are neglibible, the equation can be rewritten in the form:

$$0 = \frac{P_{s_1} - P_{s_2}}{\rho} - \frac{\bar{V}_R^2}{2g_c} - \text{losses} \qquad (3)$$

Losses are the result of friction at the surfaces, and turbulence created at expansions, contractions, and turns.

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To evaluate the losses, it is necessary to have a good physical description of the cell. It must include the lengths shown as L_1 and L_2, the cross-sectional area of the inlet stack, the shape and dimension of any noise suppression baffles in the inlet stack, and the cell cross-sectional area at the engine inlet. These can be found in engineering drawings of the test cell, or by measuring the cell. Appendix B includes a sample test cell evaluation sheet.

The loss terms that appear significant are the entry losses, losses due to flow through the baffles, expansion from the baffles into the entry stack, and the flow through the elbow. The friction losses through any unobstructed areas are two to three orders of magnitudes smaller than the above. All of these losses can be readily evaluated with the aid of the Chemical Engineers' Handbook (Reference 12).

The calculation requires a measured cell depression pressure and a Reynolds number (N_{Re}) based on estimated velocity. Cell depression is readily obtained at various fuel flows for various engines from cell operational data. The cell depression used in the equation must be an actual cell depression for the specific test cell fuel flow, and engine combination being evaluated. An initial velocity of 20 feet per second is a good approximation for the N_{Re} calculation. A second iteration of the equation may be used if 20 ft/sec is too far off.

Once the reference velocity $\bar{V}_R$ is known, it can be multiplied by the reference cross-sectional area to get the volumetric flow in ft^3/sec. Using the density of air at the cell conditions (Reference 11), the molecular weight of air, and the ideal gas law, the molar flow rate can be determined. This number, plus the number of moles of gaseous products produced by the engine combustion yields the molar flow rate at the exit plane of the exhaust stack. Using the measured exhaust plane temperature, atmospheric pressure, and the ideal gas law, the volumetric flow rate of the gases in cubic meters per second can be determined. The increase in total flow rate due to engine combustion gases is about three orders of magnitude less than total

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cell air flow rate. The air flow rate calculated above may be used directly as total cell mass flow rate. Dividing the carbon production rate by the test cell air flow rate results in a soot loading in g/m^3 at the exit plane of the cell, at actual conditions.

4. DETERMINATION OF THE PLUME OPACITY

The estimation of plume opacity is made by using the Beer-Lambert Law

$$\tau = \exp^{-(S_p \omega L)}$$

where

τ is the transmittance through the plume

S_p is the specific projected particle extinction

ω is the soot loading in g/m^3 at the stack exit

L is the path length of the beam.

The path length is obtained from the geometry of the cell, and it is the longer of the two stack dimensions. The longer dimension must be used so that the worst possible case is considered.

The selection of a value for S_p is a difficult problem. McDonald (Reference 13) reports particle diameters of 0.01μ to 0.05μ leaving the engine. Stockham and Betz (Reference 6) report that the measured geometric mean particle diameter is 0.05μ. Using 0.01μ and 0.05μ as the two extremes, and assuming monodispersed aerosols, a Brownian agglomeration calculation was done (Appendix A). This shows that agglomeration could reduce the number of particles by a factor of up to two. Agglomeration for the same mass concentration of polydispersed particles in the same size range would be considerably greater. Because of these factors, it is extremely difficult to predict particle size at the test cell exhaust.

Actual data for an evaluation of S_p is extremely limited. The only data known to this author is in work reported by Grems (Reference 9). His work measuring the particle size distribution at the exhaust plane of a test cell showed a bimodal particle distribution with a submicron mode in the range of 0.08μ to 0.2μ and then

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larger particles in the 5μ and greater range. The larger particles are thought to be the result of scouring within the test cell.

Some actual measurements of opacity versus soot loading for J-57 engines are also reported by Grems. Using known values for τ, ω, and L, values for S_p were calculated. For low smoke numbers (SN <25), S_p was in the range of 1 to 4 m^2/g and for SN >25, S_p was in the range of 7 to 9 m^2/g. Based on this information the following values for S_p are suggested:

$$SN < 25 \qquad S_p = 3\,m^2/g$$

$$SN > 25 \qquad S_p = 8\,m^2/g$$

These values are reasonable, based on the limited actual data. Predicting values using the k parameter of Ensor and Pilot requires a knowledge of geometric mean radius and geometric standard deviation, and actual physical characteristics of the agglomerated particles. Because these cannot be readily predicted, the use of the empirical results is recommended.

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

1. It is possible to predict plume opacity from known engine, fuel, and test cell parameters.

2. For the data set used, good correlation is shown between predicted and actual soot loadings. However, problems could occur because of the difficulty in predicting the specific projected particle extinction area for particles at the test cell exhaust stack.

3. Figures to evaluate the test cell predicted flow rates with actual flow rates were not available. Actual cell flow rates should be compared with the calculated values when data are available.

4. The value assigned to S_p for the final calculation of transmittance was the most likely source of error. Actual soot loadings and opacity readings were used to estimate the value for S_p, but there were so few actual readings that the data base was not considered adequate. It is anticipated that a data base will become available in the foreseeable future, and when it does, S_p must be reevaluated.

5. The estimation of plume opacity as described in this work will provide a reasonable first evaluation of test cell/engine combinations that could exceed visible emission standards. It can also be used to develop priorities for corrective action, and establish the combinations of engines and cells which would exceed standards. By shifting certain engines to different cells, violations of emission standards might be reduced with no controls required. Utilization of this type of evaluation should minimize the cost of bringing USAF Test Cells into compliance with visible emission standards.

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SECTION IV

SAMPLE CALCULATION

Calculation of Soot Loading at Engine Exhaust Plane.

	Parameters
Engine:	J-57-P21
Uncorrected Barometric Pressure:	28.72 in Hg
Inlet Air Temperature:	52°F
Fuel Flow	5340 lb/hr
Smoke Number (SAE SN):	59.5
Weight per unit Area (W/A):	0.0230 lb/in^2 (1.62 g/cm^2)
Fuel to Air Ratio:	0.0117

1. **Soot Loading (SN > 15)**

$$\omega_e/\rho_e \times W/A = 10^{(0.0263(SN)-5.96)} \, g/cm^2$$

$$\omega_e/\rho_e = 10^{(0.0263(59.5)-5.96)} \, g/cm^2 \times cm^2/1.62 \, g$$

$$\omega_e/\rho_e = 2.49 \times 10^{-5} \text{parts soot/parts exhaust (by wt)}$$

2. **Engine Flow Rates**

   5340 lb/hr x 454 g/lb x 1 hr/3600 sec x 1 mole/120 g =

   5.61 moles/sec (fuel flow)

   5.61 moles fuel/sec x 4.7 moles products/mole fuel =

   26.4 moles products/sec (product gas flow)

0.0117 lb fuel/lb air = 5340 lb fuel/x

$\quad$ x = 4.56 x 10^5 lb air/hr

4.56 x 10^5 lb air/hr x 1 hr/3600 sec x 454 g/lb x

$\quad$ 1 mole/28.97 g = 1985 moles air/sec (engine air flow)

Engine Mass Flow

$\quad$ 1985 moles air/sec + 26.4 moles products/sec =

$\quad$ 2011 moles/sec

$\quad$ 2011 moles exhaust/sec x 28.95 g/mole =

$\quad$ 5.82 x 10^4 g exhaust/sec

Exhaust particulate flow

$\quad$ 5.82 x 10^4 g exhaust/sec x 2.49 x 10^{-5} g/mole =

$\quad$ 1.45 g soot/sec

$\quad$ Assuming no losses in the test cell, soot loading at the exit plane of test cell exhaust will be 1.23 g/sec.

3. Air Flow Through the Test Cell

$\quad$ Figure 3 represents a typical test cell.

$\quad$ (English units are used because current engineering handbooks are in English units.)

Sample Dimensions

$\quad$ Inlet Area = 35 ft x 30 ft = 1050 ft^2 (overall inlet area)

$\quad$ Effective Area = A_B = 700 ft^2 (Reduced by baffles)

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31 baffles, 4 in wide, 35 ft long mounted on

    1 ft centers,

Creating 30 parallel channels, 8 in wide, 35 ft long,

    15 ft deep. (L_1)

Area E = 30 ft x 35 ft = 1050 ft^2 = 1050 ft^2 (elbow

    entrance)

    (Flow in this area will be in a square or mitered elbow.)

Area R is 30 ft x 30 ft = 900 ft^2.

Cell Depression Pressure = 0.25 in H_2O.

Velocity Relationships

$$\bar{V}_B \times A_B = \bar{V}_E \times A_E = \bar{V}_R \times A_R$$

$$\bar{V}_B = \bar{V}_R A_R/A_B = (900 \text{ ft}^2 / 700 \text{ ft}^2) \times \bar{V}_R = 1.29 \, \bar{V}_R$$

$$\bar{V}_E = \bar{V}_R A_R/A_E = (900 \text{ ft}^2 / 1050 \text{ ft}^2) \times \bar{V}_R = .857 \, \bar{V}_R$$

Losses:

a. Entry

    $F_{ent} = K_{ent} \times \bar{V}_B^2/2g_c$. Since $A_B/A_o = 700 \text{ ft}^2/\infty = 0$,

    $K_{ent} = 0.5$ for turbulent flow from Chem Engineers Handbook

    $F_{ent} = (0.5)(1.29)^2 \times \bar{V}_R^2/2g_c = 832 \, \bar{V}_R^2/2g_c$

b. Flow Through Baffles

    Hydraulic Radius = Area of Stream Cross-Section/Wetted Perimeter (for 1 channel)

    Hydraulic Diameter (D_H) = $4R_H$

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Dimension of openings for 4 in baffles on 12 in centers

= 8 in wide by 35 ft long

Area of Cross-section = 0.667 ft x 35 ft = 23.3 ft^2.

Wetted Perimeter = 2 (0.667 ft) + 2 (35 ft) = 71.3 ft.

R_H = 23.3 ft^2/71.3 ft = 0.327 ft. D_H = 4R_H = 1.31 ft.

N_{Re} = Reynolds number = D_H $\bar{V}\rho/\mu$ (Approximate Velocity

is 20 ft/sec).

ρ = air density = 0.0687 lb/ft^3 at 28.72 in Hg and

52°F.   (9)

μ = air viscosity = 1.21 x 10^{-5}lb/(ft)(sec) (Chem Eng

Handbook).

N_{Re} = (1.31 ft) (20 ft/sec) x 0.0687 lb/ft^3 x (ft)(sec)/(1.21

x 10^{-5}) lb = 1.5 x 10^5.

ϵ = surface roughness = 0.01 ft (Rough concrete is a
good approximation of the roughness of the baffles.
However, it may be necessary to calculate a better
value if the baffles are extremely rough).

ϵ/D_H = 0.01 ft/1.31 ft = 0.008

Use ϵ/D_H (0.008) and N_{Re} (1.6 x 10^5) obtain friction

factor, f = 0.009   (Chem Eng Handbook).

L = 15 ft (L-1)

F = 4 (f)(L)/D_H x $\bar{V}_B^2/2g_c$ = ((4)(0.009)(15 ft)/(1.31 ft))

x $(1.29)^2$ $\bar{V}_R^2/2g_c$

F = 0.686 $\bar{V}_R^2/2g_c$

c. Expansion from Baffles to Elbow

$$F = \overline{V}_B{}^2/2g_c \times (1-A_B/A_E)^2$$

$$F = (1.29)^2 \overline{V}_R{}^2/2g_c \times (1-700/1050)^2$$

$$F = 0.185 \overline{V}_R{}^2/2g_c$$

d. Flow Through Elbow

$$F = K_{elb} \times \overline{V}_E{}^2/2g_c \quad K_{elb} = 1.3 \text{ (Chem Eng Handbook)}.$$

$$F = (1.3)(0.857)^2 \overline{V}_R{}^2/2g_c$$

$$F = 0.955 \overline{V}_R{}^2/2g_c$$

e. Flow to Engine

30 ft x 30 ft; cross-section $A_R = 900$ ft^2

Wetted Perimeter $= (4)(30 \text{ ft}) = 120$ ft

$R_H = 900$ ft^2/120 ft $= 7.5$ ft; $D_H = (4)(7.5 \text{ ft})$

$\qquad = 30$ ft

Use same ρ, $\overline{V}$, and μ as for baffles.

$$N_{Re} = (30 \text{ ft})(20 \text{ ft/sec}) \times (0.0687 \text{ lb/ft}^3)$$

$$\times (\text{ft sec}/1.21 \times 10^{-5} \text{lb}) = 3.41 \times 10^6$$

Use ε for smooth concrete 0.001 ft

$\varepsilon/D = 0.001$ ft/30 ft $= 3.33 \times 10^{-5}$; $L = 13$ ft(L_2);

$\qquad f = 0.0025$ (from chart, Chem Eng Handbook).

$$F = (4)(0.0025)(13 \text{ ft})/((30 \text{ ft}) \times (\overline{V}_R{}^2/2g_c))$$

$F = 0.0043 \overline{V}_R{}^2/2g_c$ (negligible compared to

$\qquad$ other losses).

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Finding $\bar{V}_R$

From Eq (3), $P_{s_1} - P_{s_2}$ = Reported Cell Depression

Pressure = 0.25 in H_2O

$$0 = P_{s_1} - P_{s_2}/\rho - (\bar{V}_R^2/2g_c) - (0.832\bar{V}_R^2/2g_c)$$

$$- (0.686\ \bar{V}_R^2/2g_c) - (0.185\ \bar{V}_R^2/2g_c)$$

$$- (0.955\ \bar{V}_R^2/2g_c)$$

$$0 = (0.25\ \text{in}\ H_2O\ ft^3/0.0764\ lb)(5.2\ lb/ft^2\ \text{in}\ H_2O)$$

$$- (3.66\ \bar{V}_R^2/(2 \times 32.17\ ft\ sec^2))$$

$$0 = 17.0\ ft - (0.0569\ ft/sec^2)\bar{V}_R^2$$

$$\bar{V}_R = 299\ ft^2/sec^2$$

$\bar{V}_R$ = 17 ft/sec. Since 20 ft/sec was assumed for $\bar{V}_B$,

$$\bar{V}_B = 1.29\ \bar{V}_R = 21\ ft/sec$$

Second calculation not required.

Calculation of Volume Flow Rate i   .. cell

17 ft/sec x 900 ft² x (1m/3.28 ft)³ = 430 m³/sec

(additional volume of combustion products is
 negligible by comparison.)

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Volume flow at exit stack

Inlet temperature   =   52°F = 284°K

Exit temperature   = 120°C = 303°K

Inlet pressure   = 28.70 (barometric pressure minus
                              cell depression)

Exit pressure   = 28.72

430 m³/sec x (393/284) x (28.70/28.72) = 595 m³/sec

Soot Loading

ω = (1.45 g/sec) x (sec/595 m³) = 2.44 x 10^{-3} g/m³

Plume Opacity

τ = exp - ((8 m²/g) x (2.44 x 10^{-3} g/m³) x (10.7 m)

τ = 0.81; Opacity = 19 percent.

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APPENDIX A

AGGLOMERATION CALCULATION (13)

Length of diffuser - approximately 30 feet

Exhaust gas exit velocity at 5000 lb/hr fuel flow = 1500 ft/sec

Soot Loading 2.601×10^{-2} g/m^3

Particle diameter = 0.02μ or 0.02×10^{-6} m or 0.02×10^{-4} cm

Exhaust gas temperature = 900°F

Density of carbon = 2 g/cm^3

Volume of a particle:

$$V = 4/3 \ r^3$$

$$V = 4/3 \times \pi \times (0.01 \times 10^{-4} \text{cm})^3$$

$$V = 4.19 \times 10^{-18} \text{cm}^3/\text{particle}$$

Particles departing the engine:

$$N_O = (\text{particle}/4.19 \times 10^{-18} \text{cm}^3) \times (\text{cm}^3/2g) \times$$

$$(2.601 \times 10^{-2} g/m^3) \times (m^3/(10^2 \text{cm})^3)$$

$$N_O = 3.10 \times 10^9 \text{ particles/cm}^3$$

Evaluation of K_O, coagulation constant

Fuchs gives K_O for a 0.01 radius particle to be

34×10^{-10} cm^3/sec. It is computed at a temperature of 60°F or 520°R. To adjust for the exhaust gas temperature of 1360°R,

$$T_A/T_O \cdot K_O = 1360°R/520°R \times 34 \times 10^{-10} \text{cm}^3/\text{sec} =$$

$$8.89 \times 10^{-9} \text{cm}^3/\text{sec}$$

Evaluation of time in diffuser

The velocity at the exit of the engine is 1500 ft/sec. The gas is slowed through the diffuser so that a velocity of 1000 ft/sec will give a good estimate of residence time of the gas in the diffuser.

30 ft x sec/1000 ft = 0.03 second in diffuser

Evaluation of agglomeration:

From Fuchs:

$N = N_O/(1 + K_O N_O t)$

$N = (3.10 \times 10^9 \text{ particles/cm}^3)/(1 + ((8.89 \times 10^{-9} \text{cm}^3/\text{sec}) \times$

$(3.10 \times 10^9 \text{ particles/cm}^3) \times 0.03 \text{ sec})$

$N = (3.10 \times 10^9 \text{ particles/cm}^3)/(1 + 0.827)$

$N = 1.70 \times 10^9 \text{ particles/cm}^3$

$N/N_O = (1.70 \times 10^9 \text{ particles/cm}^3)/(3.10 \times 10^9 \text{ particles/cm}^3)$

$= 0.55$. Thus the number of particles is reduced by approximately a factor of two.

Doing the same calculation using a particle diameter of 0.05

Volume of particle:

$V = 4/3 \times \pi \times (0.025 \times 10^{-4} \text{cm})^3$

$V = 6.54 \times 10^{-17} \text{cm}^3/\text{particle}$

Particles departing engine:

$N_O = (\text{particle}/6.54 \times 10^{-17} \text{cm}^3) \times (\text{cm}^3/2\text{g}) \times (2.601 \times$

$10^{-2}\text{g}) \times (\text{m}^3/(10^2 \text{cm})^3)$

$N_O = 1.98 \times 10^8 \text{ particles/cm}^3$

Evaluation of K_O

K_O is a function of temperature: (the same as for .01)

$K_O = 8.89 \times 10^{-9} \text{cm}^3/\text{sec}$

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Evaluation of time in diffuser:

    t will not change unless fuel flow changes

Evaluation of agglomeration:

$$N = (1.98 \times 10^8 \text{ particles/cm}^3)/(1 + (8.89 \times 10^{-9}\text{cm}^3/\text{sec}) \times$$

$$(1.98 \times 10^8 \text{ particles/cm}^3) \times 0.03 \text{ sec})$$

$$N = 1.88 \times 10^8 \text{ particles/cm}^3$$

$$N/N_o = 0.95 \text{ (no significant agglomeration)}$$

TEST CELL INFORMATION SHEET

1. The information requested will be used to assess the environmental impact of test cell operations at your base. The information is required only once for each type of test cell.

2. You may use schematic drawing (Figure B-1) of a typical test cell to supply required test cell dimensions. Simply write in the dimension indicated beside each of the double headed arrows. Cross-section A-A on the schematic corresponds to the overall area of the inlet stack entrance. Cross-section B-B is the area of the cell exhaust stack. Cross-section C-C corresponds to the area around the cell depression pressure probe (usually at the engine intake).

3. If the cell has any special features or if it differs from the sketch, feel free to modify the sketch as required, labeling the changes clearly.

4. In addition to the dimensions requested on the sketch, please answer the following questions:

     a. How is the cell identified? (e.g., Bldg Number, site number, etc.)

     b. What type of engines are run in this cell? List each type. (e.g., J-57-P21 A)

     c. How far in front of the engine is the cell depression probe? Indicate on schematic diagram.

     d. Where is the compressor inlet temperature probe? Indicate on schematic diagram.

     e. How many cooling water rings are there? Where are they located? (Mark on sketch W_1, W_2, W_3, etc.) and give distances from an identified point.

     f. Does the air intake have baffles? If possible, send a copy of the plans showing the baffles.

     g. If the baffle plans are not available, please make a sketch showing their locations in the intake, the shape of

the baffles, and their dimensions. Be sure to include the following:

        (1) Number of openings for inlet air (spaces between baffles).

        (2) Length and width of each baffle opening.

        (3) Depth (how far do baffles extend into inlet stack?)

    h. How far below the exhaust stack exit is the exhaust gas temperature probe?

    i. Line A-B on the sketch represents a small wall that sometimes protrudes into the horizontal portion of the cell from the top, sides, and/or floor. This is normally between the intake stack and horizontal portion of the cell. If there is a restriction of this type, give us the cross-sectional dimensions of the cell at this point, as well as at the cell depression probe.

        Restricted Height_____   Width_____

        Thickness of Protrusion _____

    Again, the cell information requested must only be provided once. Please try to make it as accurate and complete as possible. In particular, the cell depression pressure must be measured as carefully as possible. The decision to implement a smoke reduction program for your test cells depends largely on this information.
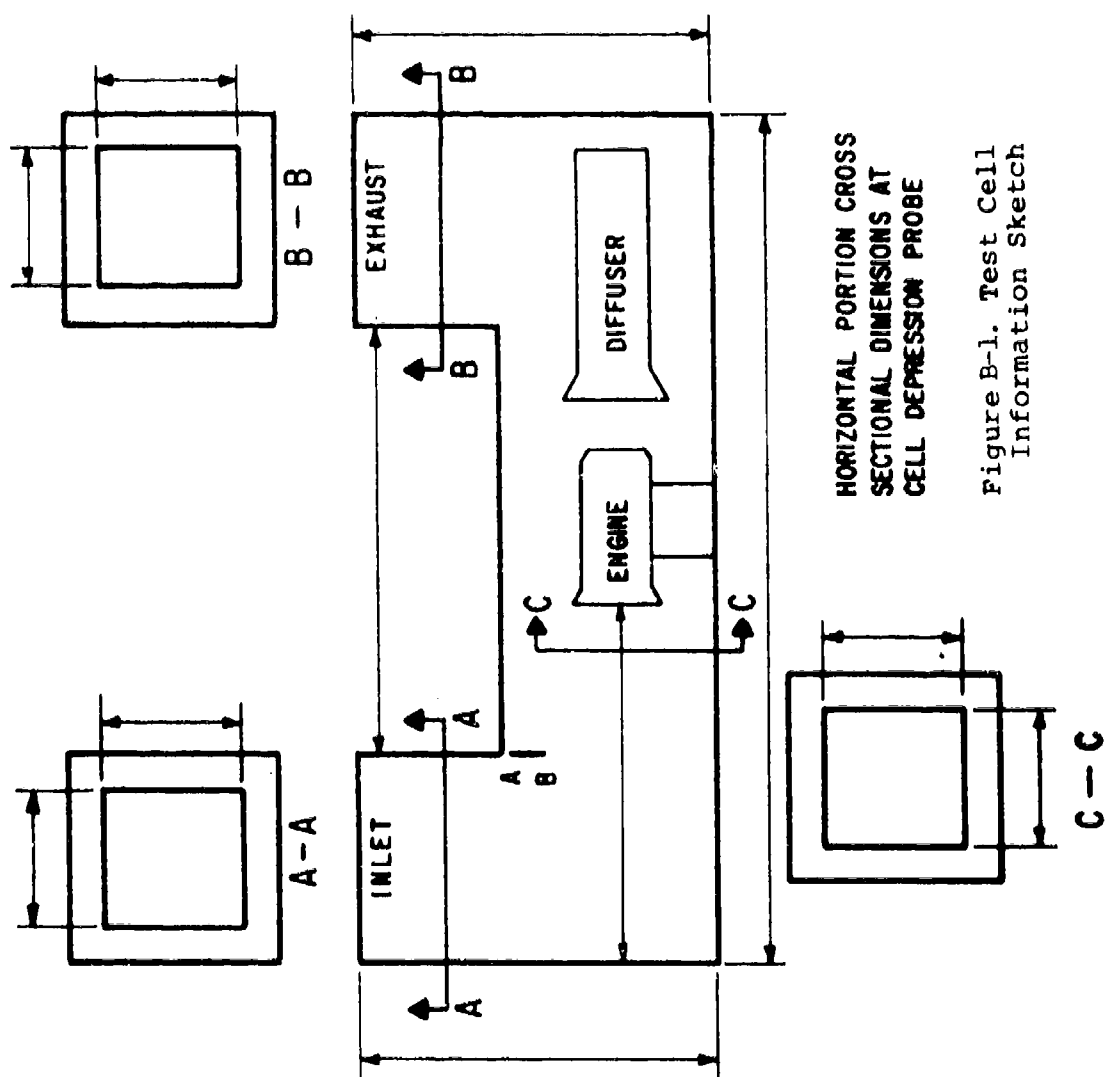
HORIZONTAL PORTION CROSS
SECTIONAL DIMENSIONS AT
CELL DEPRESSION PROBE

Figure B-1. Test Cell
Information Sketch

CELL IDENTIFICATION:_____
        BASE:_____

APPENDIX C

FLOW CHART FOR CALCULATION OF PREDICTED OPACITY

The simplified flow chart on the following pages indicates
the most efficient method of computing the predicted opacity
for a given test cell and engine combination. This general
scheme was used in the development of a computer program
written in FOCAL for the PDP-8 minicomputer.[1]

The computations are divided into two main parts. Since
the friction losses for a given test cell are constant regard-
less of the engine used, these are calculated first. Using
test cell dimensions, the loss is computed for each contraction,
expansion, baffle, and elbow encountered by the air as it flows
from the test cell inlet to the engine intake.

The total friction losses are then used to calculate the
velocity and, hence, volume of air flow in the reference section
of the test cell, using the measured cell depression for a given
engine operation. The other measured parameters for that engine
operation, i.e., SAE SN, Fuel Flow, Fuel/air ratio, are used to
calculate the particulate concentration in the test cell exhaust
which, in turn, is used to compute a predicted opacity.

The detailed calculations referred to in the flow chart
may be found in Section IV of this report, "Sample Calculations."

_____

[1] A copy of the program may be obtained by contacting the
Division Chief, AFCEC/EVA, Tyndall AFB FL 32403.

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MAIN FLOW CHART

```
        ( A )
          │
          ▼
┌─────────────────────────────────┐
│  Enter baffle channel dimensions │
└─────────────────────────────────┘
          │
          ▼
┌─────────────────────────────────┐
│      Compute $R_H$ and $D_H$     │
└─────────────────────────────────┘
          │
          ▼
┌─────────────────────────────────┐
│   Enter estimate of velocity in  │
│        reference section         │
└─────────────────────────────────┘
          │
          ▼
┌─────────────────────────────────┐
│     Compute Reynolds number      │
└─────────────────────────────────┘
          │
          ▼
┌─────────────────────────────────┐
│   Enter fanning friction factor  │
└─────────────────────────────────┘
          │
          ▼
┌─────────────────────────────────┐
│   Compute friction loss for      │
│  baffle flow and add to total    │
│        friction loss             │
└─────────────────────────────────┘
          │
          ▼
        ( E )
```
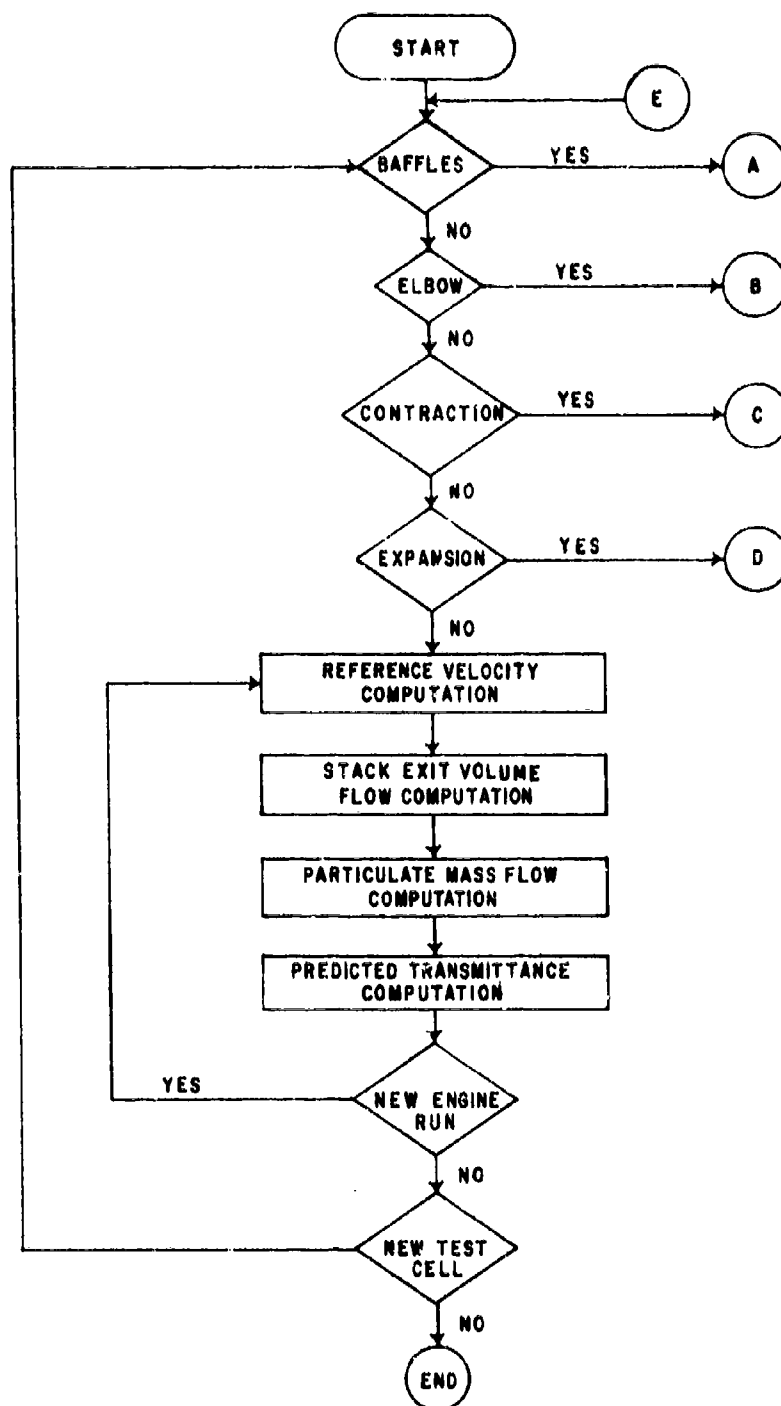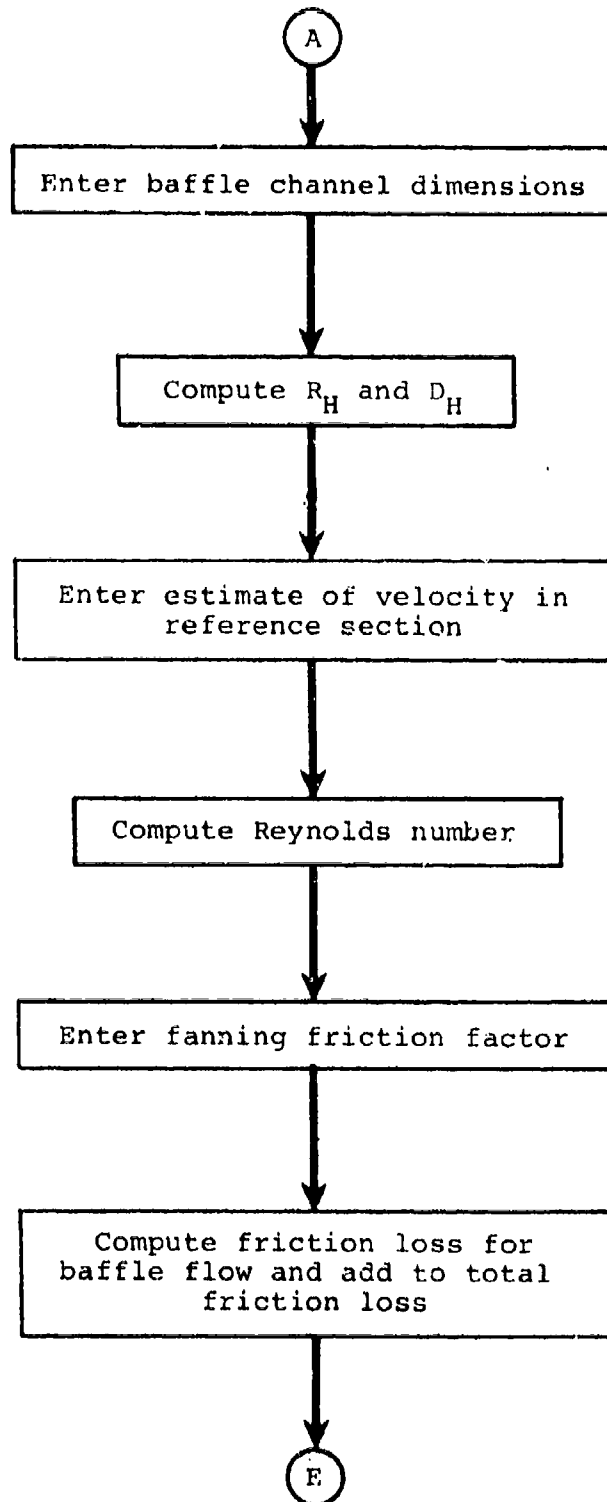
Baffle Flow Friction Loss Procedure

32

(B)

```
┌─────────────────────────────────┐
│  Determine constant (K) for given │
│    degree of bend (45°, 90°, etc) │
└─────────────────────────────────┘
```

```
┌─────────────────────────────────┐
│     Compute friction loss for     │
│       flow through elbow and      │
│    add to total friction loss     │
└─────────────────────────────────┘
```

(E)

Elbow Friction Loss Procedure

(C)

```
┌─────────────────────────────────┐
│   Enter areas (expanding from     │
│      Area A into Area B)          │
└─────────────────────────────────┘
```

```
┌─────────────────────────────────┐
│     Compute friction loss for     │
│         expansion flow            │
└─────────────────────────────────┘
```
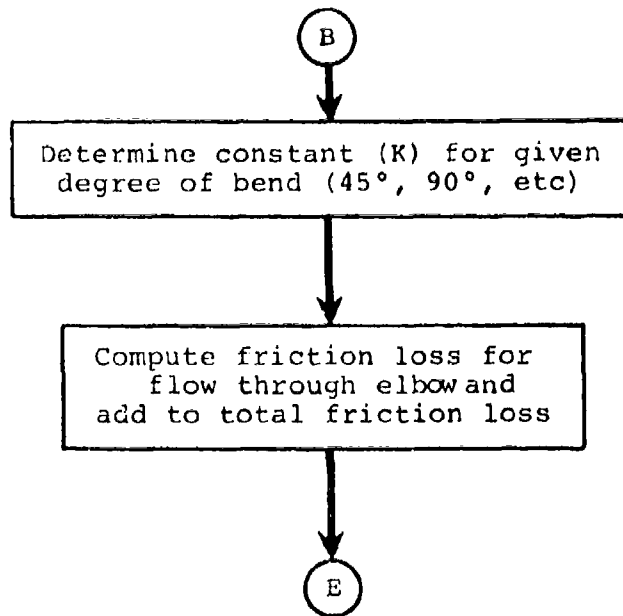
(E)
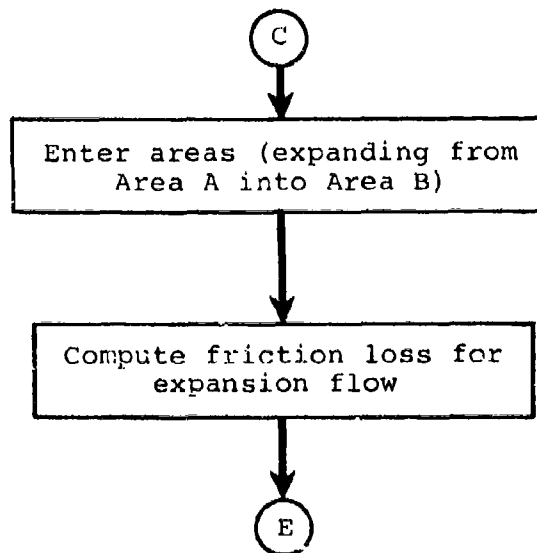
Expansion Friction Loss Procedure

```
                         ┌───┐
                         │ D │
                         └───┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │    Enter areas (contracting from  │
        │        Area A into Area B)         │
        └──────────────────────────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │   Determine constant, K, from     │
        │          ratio of areas           │
        └──────────────────────────────────┘
                           │
                           ▼
        ┌──────────────────────────────────┐
        │   Compute friction loss due to    │
        │         contraction of flow       │
        └──────────────────────────────────┘
                           │
                           ▼
                         ┌───┐
                         │ E │
                         └───┘
```
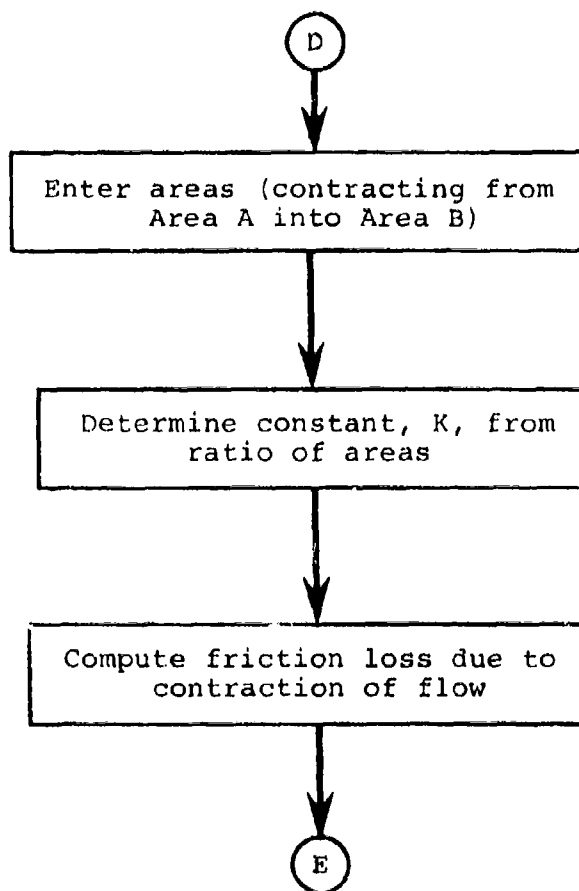
Contraction Friction Loss Procedure

Reference Velocity Computation

> Use total friction loss, air density, cell depression pressure and reference section cross-sectional area to compute volume flow in reference section in m^3/sec.

Exit Stack Volume Flow

> Use compressor inlet temperature, exit stack temperature, exit stack pressure, and cell depression pressure to compute volume flow at exit stack.

Particulate Mass Flow

> Use SAE SN, fuel flow, and fuel/air ratio to compute particulate mass flow at engine exhaust in g/sec.

Predicted Transmittance

> Use stack exit volume flow and particulate mass flow to determine particulate mass concentration in g/m^3. Use this value along with plume width to calculate percent transmittance.

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